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A Next Generation SmallSat Lidar Concept for Atmospheric Science and Opportunities for Multi-Sensor and Modeling Synergy for Aerosol Retrievals

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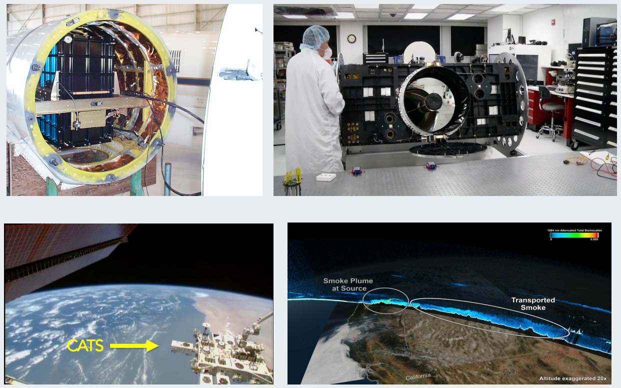
Introduction

Aerosols play a key role in the Earth's atmosphere by interacting with the Earth's radiation budget, modulating clouds and precipitation, atmospheric dynamics, geochemical cycles, and serve as a major source of poor air quality. To properly understand these interactions with the Earth system, determining the vertical distribution of aerosols is critical. While previous spaceborne elastic backscatter lidars such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) and the Cloud-Aerosol Transport System (CATS) have provided such critical measurements of aerosol vertical distributions, here we present a low-cost, low-risk, dual wavelength SmallSat elastic backscatter concept that can be readily implemented as part of future NASA Earth-Venture and the Atmospheric Observing System (AOS)/Planetary Boundary Layer (PBL) Decadal Survey missions. We refer to the free-flying SmallSat version of our instrument as TOMCAT (Time-varying Optical Measurements of Clouds and Aerosol Transport) and as ALICAT (Atmospheric Lidar Instrument for Clouds and Aerosol Transport) to be flown with other instruments on a larger spacecraft for AOS.

Instrument Heritage

Our instrument utilizes a low energy - high repetition rate - photon counting measurement approach that has over 20 years of heritage from our airborne Cloud Physics Lidar (CPL) that primarily has operated on the NASA ER-2, as well as the NASA WB-57 and Global Hawk. CPL led to the development of the Cloud-Aerosol Transport System (CATS) that flew as a technology demonstration on the International Space Station for 33 months from 2015-2017. Despite providing useful science data primarily from a single wavelength, the CATS design was bulky, roughly the size of a household refrigerator, and was limited in transmitted laser energy due to ISS safety requirements.

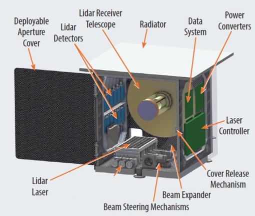


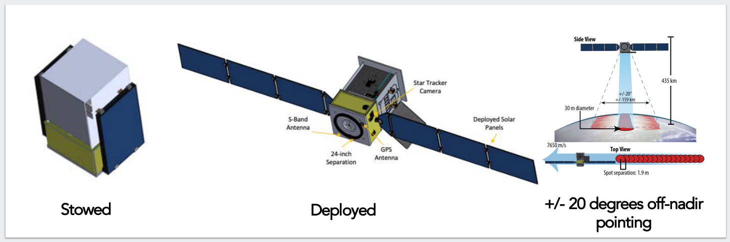
CPL integrated on the NASA ER-2 aircraft (top left), CATS in the lab at NASA GSFC (top right), CATS on the ISS (bottom left), and CATS measurements of smoke from Pacific Northwest fires.

Instrument Description

NASA Earth Science Technology Office (ESTO) and the NASA Small Business Innovation Research (SBIR) support enabled development of a SmallSat laser transmitter suitable for use on an ESPA-compatible SmallSat. The CATS design was further modified to be ESPA compatible for SmallSat implementation as a free-flyer. No longer restricted to ISS safety requirements, transmitted laser energy was increased and the mass and volume of the laser optical head and data system significantly reduced. All major subsystems are at technical readiness level (TRL) 6 or greater. In the TOMCAT design, the instrument also has the ability to point +/- 20 degrees off-nadir for targets of opportunity.

Parameter	Value
Laser type	Nd:YVO_4
Laser wavelengths	1064 and 532 nm
Depolarization	1064 and 532 nm
Laser repetition rate	4 kHz
Laser pulse energy	3 mJ at 1064 nm, 2 mJ at 532 nm
Laser pulse length	~10 ns
Transmitted beam divergence	70 μrad (1064 nm) / 35 μrad (532 nm)
Telescope diameter	60 cm
Telescope field-of-view	115 μrad (1064 nm) / 85 μrad (532 nm)
Vertical resolution	30 m or 60 m
Horizontal resolution	20 Hz, or 350 m along-track

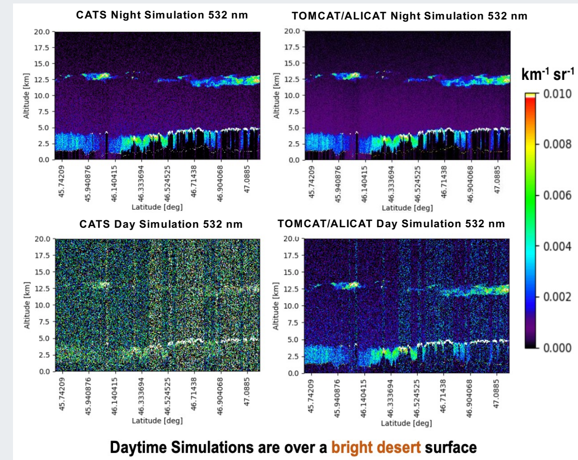




TOMCAT/ALICAT instrument specifications (top left), instrument design (top right), and configurations when stowed, deployed, and pointing off-nadir as a free flyers (bottom row).

Instrument Performance

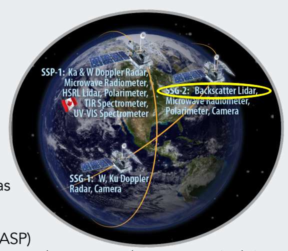
Owing to the increase in transmitted laser energy and improvements to receiver aft-optics, TOMCAT/ALICAT exhibits higher signal-to-noise ratios (SNR) compared to CATS. This is particularly evident during bright daytime scenes, where the daytime 532 nm SNR is 4-8 times greater than CATS.

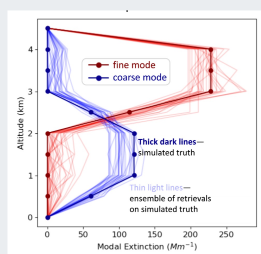


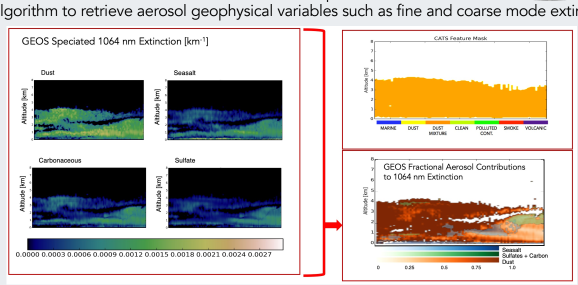
CATS (left), TOMCAT/ALICAT (right) nighttime (top), and daytime (bottom) 532 nm performance comparisons for an aerosol and cloud scene over desert. Significant improvements in TOMCAT/ALICAT SNR translates to less-noisy measurements of total attenuated backscatter during the day.

Opportunities for Synergy with Passive Sensors and Aerosol Models

Recently, ALICAT was named as the backscatter lidar for the upcoming AOS Decadal Survey mission and is anticipated to launch in 2028 (left). A capable polarimeter is planned to fly with ALICAT in the AOS inclined orbit. During daytime, aerosol optical depth (AOD) measurements provided by a polarimeter or geostationary sensors (e.g. GOES-16) can provide a constraint on the lidar ratio when retrieving extinction, offering a more advantageous approach to assuming a default lidar ratio when constrained retrieval methods such as the transmission loss method cannot be used. Preliminary joint ALICAT+polarimeter retrievals are underway using the Generalized Retrieval of Aerosol and Surface Properties (GRASP) algorithm to retrieve aerosol geophysical variables such as fine and coarse mode extinction (right).





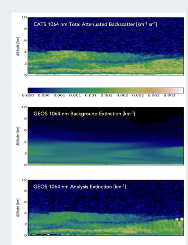


Information content on the lidar ratio can also come from global aerosol transport models. Traditional spaceborne aerosol typing algorithms assign an aerosol type and a corresponding lidar ratio based on measurements (e.g. depolarization ratio) and ancillary information such as surface type. From CATS, we have developed the infrastructure to pull aerosol profiles from the NASA GEOS model to inform aerosol typing and lidar ratio choice in near-real time. The information content provided by GEOS can be particularly useful for assigning lidar ratio for aerosol mixtures. In this example, GEOS can provide a dynamic lidar ratio when the traditional algorithm would assign a default value.

Enabled Applications

One novel aspect of CATS was the ability to downlink and process spaceborne lidar data in near-real time (< 6 hours). For TOMCAT/ALICAT, we anticipate NRT data products within 3 hours. This low latency is critical for the numerous modeling/forecasting communities who can utilize aerosol vertical profile information as a constraint for improving aerosol transport forecasts. In particular, the low-cost SmallSat design of TOMCAT naturally lends itself to a constellation approach enabling improved coverage at different times of the day compared to a single sun-synchronous sensor.

During CATS operations, NRT products were used to develop preliminary 1-D ensemble-based variational (1-D EnsVar) techniques for operational data assimilation in global aerosol transport models offering improved vertical structure in aerosol extinction. Operationally, this technique can be further developed to provide a powerful constraint on global aerosol transport model forecasts, particularly if a constellation of TOMCAT lidars is employed for enhanced sampling at different times of the day.



Summary

- We have developed a next generation dual wavelength elastic backscatter concept that provides polarization sensitive measurements from a SmallSat platform (TOMCAT). The concept will also be the backscatter lidar in the future AOS Decadal Survey mission (ALICAT).
- Despite the smaller package, the TOMCAT/ALICAT instrument design offers significantly better SNR during the daytime compared to the CATS technology demonstration.
- The compact, low-cost design of TOMCAT/ALICAT enables a constellation approach for increased sampling that will greatly benefit the applications community.
- Future spaceborne lidar missions have the opportunity to advance beyond traditonal lidar-only algorithms and reap the benefits of constraints and information content provided by passive sensors and global aerosol transport models.